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Innovation and Education

NON-EMPIRICAL RESEARCH

The S-T-E-M Quartet

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Abstract

The issue of integrated STEM curriculum design and evaluation requires a more consistent understanding and clarity among STEM educators. In this paper, we propose an instructional framework of STEM integration based on the theoretical notions of disciplinarity and problem-centred learning. The proposed S-T-E-M Quartet instructional framework utilises complex, persistent and extended problems at its core, and the problem solving process as the overarching frame. The key difference between the proposed S-T-E-M Quartet instructional framework and models such as the STEM road map and the Cubic model for STEAM education is the emphasis on the connections between different disciplines. Similar to the STEM road map, the application of the S-T-E-M Quartet framework begins with a single lead discipline as the focus and subsequently examines how knowledge and skills of the lead discipline are connected and related to the other three disciplines. As an instructional framework, the S-T-E-M Quartet requires description of learning outcomes for each discipline when students work with the problem. The learning outcomes within individual disciplines constitute the vertical learning within a discipline. Depending on the problem described, the learning outcomes for some disciplines might be more in-depth than others. As the S-T-E-M Quartet foregrounds connections between disciplines, attention is also paid to the strength of connections, whether they are weak, moderate or strong. A case example of application of the S-T-E-M Quartet instructional framework is presented as an illustration of how the S-T-E-M Quartet instructional framework can be used to design and reflect on STEM tasks.

Keywords: Integration, Instructional framework, STEM, Cross-disciplinary, Problem solving

Introduction

This paper presents an instructional framework for designing and evaluating STEM activities from the perspective of disciplinarity and problem solving. STEM, an acronym for science, technology, education and mathematics, has received much attention over the years in different countries for its potential to improve the relevance and quality of science and mathematics education (Honey et al. 2014). A good STEM education is touted as the solution to produce innovative thinkers for STEM-related industries to support the global economy. Besides preparing students for the future workforce, STEM education is crucial for the personal development of individual students to enable them to make sense of a world (Marrero et al. 2014) that is increasing powered by science and technological innovations. Despite the attention paid to STEM education, there is little consensus on what constitutes STEM and how STEM outcomes can be measured (Bybee 2013; Honey et al. 2014). Kelley and Knowles (2016, p. 1) concurred by highlighting that "STEM educators lack cohesive understanding of STEM education." In a comprehensive report on STEM education, Honey et al. (2014, p. 2) highlighted that there is "little research on how best to *integrate* or on what factor makes integration more likely to increase student learning, interest, retention, achievement, or other valued outcomes." With differing understanding of the characteristics of STEM (in particular integrated STEM) and affordances of STEM education, policy makers, educators and members of the community could potentially misunderstand policy intentions and results from educational evaluation. To increase clarity in what integrated STEM is and aspects of integrated STEM lessons to be evaluated, we propose an instructional framework to enable teachers to plan integrated STEM activities that takes into consideration the vertical learning within individual specific disciplines and at the same time reflects the horizontal connections across the disciplines. The attention

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we place on the connections between the four disciplines is deliberate as this has been flagged as an area requiring attention, particularly in current integrated STEM curriculum where connections between the disciplines are largely implicit. To increase clarity in the definition of integrated STEM and the aspects of integrated STEM lessons that should be evaluated, we propose an instructional framework that addresses the depth and breadth of STEM learning that emphasizes both the learning *within* individual disciplines as well the connections *between* the disciplines.

Theoretical background

Disciplinarity

Learning in many disciplines has traditionally been defined by unique knowledge and practices within clearly marked parameters. As such, knowledge across different disciplines, for example the sciences and social sciences, are often thought to be different from each other (Becher 1987/1989; Biglan 1973; Pantin 1968). The sciences have been viewed as a field of study that is more systematic and predictable while the social sciences are perceived to be more varied and less predictable (Becher 1989). In fact, as early as 1989, Becher noted that disciplinarity and institutional boundaries between sciences and humanities, between natural sciences and human sciences, between public discourses of science and folk wisdom have already been subjected to scrutiny. This same level of scrutiny of discipline boundaries is needful in our consideration of integrated STEM curriculum in schools.

Definitions of what constitutes a discipline are varied. For instance, King and Brownell (1966), in their account of disciplines, examined ideas of a community, a network of communications, a tradition, a particular set of values and beliefs, a domain, a mode of enquiry, and a conceptual structure of disciplinary knowledge. Toulmin's (1972) idea of a discipline focuses on epistemological considerations and characterizes disciplines by bodies of concepts, methods and fundamental aims. Other researchers such as Whitely (1976, 1984) viewed disciplines as organized social groupings while Shinn (1982) added the need to include social elements in the epistemic and cognitive schema of disciplinary knowledge.

The various attributes such as cognitive, epistemic, social and conceptual structures of a discipline can be distinguished from one another as stable and separate entities (Becher 1989). Further to this, the boundaries of a discipline are subjected to historical and geographical variations and as such, changes in discipline domains over time produces different identities for the disciplines and their practitioners. New discipline groupings, demise of old discipline groupings and disciplines in mid-cycle transitions will impact how practitioners and researchers of the disciplines examine and approach academic disciplines. This idea of changeable structure of a discipline is an important one for our discussion on integrated STEM. The disciplines of science, technology, engineering and mathematics are traditional stand-alone disciplines with their own unique conceptual, epistemic and social constructs, at least in academic settings. In the attempt to design integrated STEM curriculum, it is fundamental to question and examine how the traditional boundaries of each domain can be changed and if integrated STEM can be considered an independent discipline that possesses its own unique practices and epistemic constructs.

To explore the idea of discipline boundaries and how it affects our idea of integrated STEM, consider the suggestion by Toulmin (1972). He suggested that different disciplinary fields exist on a continuum that ranged from compact to diffused. Compact disciplines are characterized by an agreed goal or ideal and outstanding problems which can be identified. For instance, in science, scientists working in a specific research area may not necessarily agree upon the validity of particular theories but they typically agree on the questions to address. Similarly, mathematicians generally have a common agreement of what a proof of a theorem is even though they may work in different mathematical fields. Diffused disciplines, however, are characterized by the absence of clearly defined goals, ideals or problems. MacDonald (1994) enhanced Toulmin's idea of the variation in disciplinary domains to suggest four patterns of variation ranging from/in: (1) compactness to diffuseness, (2) explanatory and interpretative goals, (3) conceptually-driven to text-driven, in relation to generalization and the particular; and (4) the degrees of epistemic self-consciousness that are explicit in texts. Existing ways of characterizing disciplinary boundaries have limitations in its application in schools since disciplinary knowledge is typically packaged into curricular content in educational institutions. For Bernstein (1977), curriculum refers to the valid knowledge that a school system embodies and aims to transmit to the next generation. As such, he classified curriculum knowledge on a continuum from a collection of bodies of knowledge on the one end with the integration of knowledge on the other end. Bernstein distinguishes the boundary between contents of different curriculum knowledge which he termed 'classification.' Strongly classified curriculum knowledge refers to those that are well-insulated from one another (Bernstein 2000). Each category has their own unique voice, specialized rules and special identity. Categories with weak classifications have less specialized discourses, identities and voices.

According to the National Research Council (NRC) (2009), science as a discipline focusses on the study of the natural world that includes the laws of nature. The body of knowledge in science is generated through the process of scientific inquiry and is accumulated over time. Scientific knowledge can be used to inform engineering design processes. Technology as a field is probably one that is most diffused in terms of the problems or issues unique to the discipline. Historically, technology is a system to create artefacts that can be applied to solve problems to make life simpler. Engineering as a discipline consists of both the knowledge about design and creation of human products and developing processes of problem solving. In designing products and devising solutions to problems, engineering applies scientific and mathematical concepts together with technological tools. Finally, mathematics is a discipline that delves into the study of patterns and relationships among quantities, numbers, and space. The unique feature of mathematics is that claims are warranted through logical arguments based on foundational assumptions instead of empirical evidence. Hence, knowledge in mathematics is not overturned unless the assumptions on which it is built on are changed.

The theoretical ideas of disciplinary boundaries of knowledge from one that is compact (strongly classified) to one that is diffused (weakly classified) can be applied to examine and design integrated STEM learning. Disciplines in STEM are mostly strongly classified or compact discipline with unique practices, conceptual constructs and ways of thinking. In integrated STEM, what researchers are trying to do is to blur the boundaries defining the four disciplines and apply them in such a manner that will mutually enhance the practices of individual disciplines. We argue here that integration efforts need to be carried out with great thought so as not to compromise the intended and established epistemic, conceptual and social norms of each discipline.

Clarifying STEM

The acronym STEM began with the National Science Foundation (NSF) in the United States as a convenient and efficient way to identify and communicate the four disciplines (Bybee 2013). With time, the term STEM has been used largely by policy makers and curriculum developers to refer to educational outcomes "related to knowledge economies, technical innovations, the basis for businesses and industries to thrive, the competencies for a twenty-first century workforce, and national security." (Bybee 2013, p. 74). This broad and diffused understanding of STEM presents complexities in design, implementation and evaluation of STEM programs. It hence becomes necessary to clarify the meaning of STEM for practitioners and educational researchers.

In the recent two decades, learning about STEM education has gained traction worldwide as cross-disciplinary (compared with mono-disciplinary) knowledge and skills are valued in modern times to meet the demands of the fourth industrial revolution and a world that is increasing characterized by the blurring of disciplinary divides and technological infusion. The advent of the fourth industrial revolution places importance on digitization and technology in human life and communities. Their impact on and transformation of the lives of ordinary people have never been more significant. Yet, despite the overwhelming outputs of STEM knowledge and artefacts, the abilities of our educators and young people to take advantage of new opportunities that the world have to offer remained diffused (Koh 2018). The complex problems (such as climate change and cyber threats) faced by the world today require knowledge and skills from different disciplines to appreciate and understand the issues in order to live and participate in the world in a meaningful manner. Beyond preparing the future work force, the need for every citizen to understand and play their part to combat the complex problems of the world provide the compelling (while pragmatic) reasons for embracing integrated STEM education in schools.

Structural limitations for implementation of integrated STEM

To enable deeper connections among the four STEM disciplines, reforms such as the Next Generation Science Standards in the US advocated for purposeful integration across the disciplines (NGSS Lead States 2013). Bryan et al. (2016, p. 23) defined integrated STEM as the "teaching and learning of the content and practices of disciplinary knowledge which include science and/or mathematics through the integration of the practices of engineering and engineering design". They suggested that integration could be achieved through incorporation of content or context. Sanders (2009, p. 21) described integrated STEM as "approaches that explore teaching and learning between/among any two of more of the STEM subject areas, and/or between a STEM subject and one or more other school subjects". Sanders' definition of STEM education is broader and more encompassing when compared to Bryan et al. (2016) which focusses more specifically on the content and practices of science and mathematics supported by engineering practices. Being more focus, Bryan et al.'s ideas could make it clearer for STEM educators to understand what integrated STEM is. Kelley and Knowles (2016) also attempted to make sense of integrated STEM and their definition has elements of ideas from both Sanders (2009) and Bryan et al. (2016). Integrated STEM is defined as approaches to teaching STEM content of two or more STEM disciplines, guided by STEM practices within an authentic context to enable connections to be made between the disciplines (Kelley and Knowles 2016). Regardless of the definition of integrated STEM adopted, issues with implementation appear to persist.

The knowledge of how STEM education can be operationalized remains lacking among teachers (Kelley and Knowles 2016). Many K-12 school systems are organized around subjects. As such, students attend science classes, mathematics classes, technology classes and even design classes. Each class is taught by a teacher who is a specialist in the discipline area, that is, a science teacher, a mathematics teacher or a design and technology teacher. School schedules are also designed such that there is individual class time for students to interact with the various subject teachers. Further, assessment of learning in schools is still largely subject based and hence, teachers will be teaching content and skills required within a single discipline. For instance, students will sit for a science test, a mathematics test or an engineering and design test. These assessments will also be graded by teachers who are specialists within a single discipline. Current school schedules support mono-discipline forms of learning and interaction. Consequently, multi- or cross-disciplinary learning opportunities require deliberate efforts to plan and organize, and thus are infrequently carried out.

Besides the organisation of learning by subjects, teacher education is another factor to consider in integrated STEM education. Currently, there are few systems that have a school subject called STEM or have certified and qualified STEM teacher education programmes. In fact, there are few pre-service teacher preparation programmes that train integrated STEM teachers. Therefore, to expect a science or mathematics teacher to carry out a truly integrated STEM curriculum that require in-depth knowledge of engineering and use of technological tools is unrealistic. Given the absence of teachers with the skills and knowledge of all four disciplines, integrated STEM models requiring knowledge and skill sets from all the four disciplines are not likely to work in current structural organization of K-12 schools whereby subjects are taught mainly by one teacher. To facilitate teaching of integrated STEM, teachers will need to plan and teach in teams. The formation of integrated STEM teaching teams will require educational administrators to schedule time and space for teaching teams to come together to engage in professional dialogue to share discipline expertise as well as to develop synergy and understanding of different disciplines.

Given the structural limitations of current school structures, curriculum, and pre-service teacher education, we explore existing models of integrated STEM education to enable us to better understand the features of existing models takes that could overcome the hurdles described.

Models for integrated STEM education

The current state of STEM education research is limited in integration (Choi and Pak 2006). Based on a recent review of 152 peer-reviewed journal articles published in STEM or science education journals, 106 papers (70%) were mono-disciplinary in that the curriculum is either S/T/E/M. Of the remaining papers, only 10% were multidisciplinary, 14% were inter-disciplinary, and 6% were trans-disciplinary. The diversity in the types of research that has been published in STEM or science education journal points to the need to develop a more robust and shared understanding of integrated STEM and its relevance to modern day education goals. STEM education researchers have also not established a common consensus on how integration of the disciplines in STEM can be achieved. In this section, we present four existing models of STEM integration and discuss the strengths and weakness of each of these models when seen in the light of the structure of schools, particularly in Singapore.

Framework for STEM integration in the classroom

To support the STEM Road Map project in America, Moore et al. (2014) crafted the *Framework for STEM integration in the classroom* to provide a foundation for meaningful integration of the STEM disciplines. The *Framework for STEM integration in the classroom* advocated the use of real-world contexts, challenges and problems to provide opportunities for students to learn in an inter-disciplinary manner. In promoting integration across the curriculum, engineering practice and design is used as mechanism for integration. This framework takes into consideration learning within science and mathematics using engineering design and practices. This framework also allows for a lead discipline when designing lessons. Through engagement with authentic problems, teachers will emphasize learning of twenty-first century skills. This framework presents STEM as a teaching and learning approach and teachers using this approach work through the strategies they like to engage students while solving the problems. Using this approach, teachers map the learning outcomes to the standards in NGSS. As this framework uses engineering design as integration mechanism, it does not discuss explicitly how the disciplines are connected.

Situated STEM learning

Using the theoretical lens of situated cognition, Kelley and Knowles (2016) proposed a model for integrated STEM education that focusses on creating experiences that are representative of actual STEM practice. This framework is presented as science inquiry and engineering design linked to technology and mathematics. Unique to this framework is the emphasis on situated STEM learning and the inclusion of a community of practice. The learning experience serves as the integration mechanism in this model. In presenting their model, Kelley and Knowles did not focus their ideas on how the conceptual knowledge and epistemic knowledge from each discipline interact during the learning experiences. The formation of communities of practices serves to fulfil the social outcomes within each discipline.

The Society-Technology-Science-Society (STSS) model

This STSS model was mentioned by Banks and Barlex (2014) in their discussion on how STEM integration can be done. According to Banks and Barlex, the STSS was developed by ORT (a non-governmental Jewish education organization). The STSS focusses on problem-solving using social scientific and technological knowledge. In this model, they view science and technology as distinct yet interacting disciplines (Banks and Barlex 2014). The needs of the society and how the solutions generated impact the society forms the focus in this model. Integration is achieved through applying science and technology to create solutions to solve societal problems. Similar to the situated STEM learning model proposed by Kelley and Knowles, the focus here is on the outcome of problem solving and the impact on the society. The STSS model is beneficial to helping students develop empathy as well as skills for the twenty-first century.

Learning standards framework of STEAM classes

The Korean Foundation and for the Advancement of Science and Creativity (2016) maps out the Learning Standards Framework of STEAM classes. This framework has three key components of context, creative design and emotional touch. The integration is through the problems and new problems that are generated with every new solution. Through the process of problem solving, students will apply the skills and knowledge of the different disciplines. Engineering concepts is included in the framework to refer to technological design and the stimulus for creative problem-solving to enable the development of shared values of humanity (Park et al. 2016). The focus on creative design afforded open-endedness and collaboration in the learning process for STEAM in the Learning Standards Framework of STEAM classes. The overall positive learning experiences of individual learners is taken into account with attention paid to the affective factors, emotional touch and collaborative teams. Similar to STSS model, the Learning Standards Framework of STEAM Classes focuses on the learner and aims to "provide innate rewards to students through creative design, emotional touch, and content convergences and integration" (Park et al. 2016, p. 1743).

Table 1 provides a summary comparison of the key features of the different models described. While each of the framework is developed to meet educational needs and demands of different educational systems, there is a common focus on the use of problems as a means to engage students in STEM, although the integration mechanism differs. Taking the structural limitations to implementation of STEM into consideration, we argue that the framework for STEM integration in the classroom (Moore et al. 2014) is likely to be most comprehensive in how integrated STEM can be organized for implementation. The affordance of having a lead discipline allows for any single of any discipline to take charge of the STEM lessons. This helps to overcome the ownership issue in STEM implementation. The situated STEM Learning model does not detail the integration mechanism across the disciplines. The

Table 1 Summary comparison of existing STEM education models

Models	Framework for STEM integration in the classroom (Moore et al. 2014)	Situated STEM Learning (Kelley and Knowles 2016)	STSS (Banks and Barlex 2014)	Learning Standards Framework of STEAM Classes (Korea Foundation and for the Advancement of Science and Creativity 2016)
Areas of focus				
Authentic real-world problems	Yes	Yes	Yes	Yes
Engineering practice and design as means of integration	Yes	Yes	No	No
Standard based learning outcomes is considered	Yes	No	No	No
Science inquiry	Limited	Yes	No	Yes
Twenty-first century skills	Yes	Limited	Yes	Yes
Consideration on context	Limited	Yes	No	Yes
Connections between disciplines	No	No	No	No

value of the model is the focus on building a community of practice. The STSS and Learning Standards Framework of STEAM Classes emphasise the development of positive learners' experiences and empathy for the environment and the society through engagement with contemporary societal issues. With the focus on the affective and twenty-first century learning, there is proportionally lesser emphasis on the learning outcomes of the disciplines of science, mathematics, engineering and technology. Across the models, there is little mention on how the different disciplines are connected explicitly. The seemingly lack of explicit focus on how disciplines are connected was highlighted by Honey et al. (2014) in their review of STEM research and programmes in America. They recommended that reasearchers could devise ways to enable teachers and students to pay attention to now conceptual knowledge, epistemic practices and social outcomes are related across disciplines. In this paper, we attempt to address this gap by building on the affordances of existing models and suggest a way for teachers to help learners understand the connections between different disciplines.

Using affordances from existing integrated STEM models, we propose an instructional framework for integrated STEM that is centred around complex, persistent and extended problems. The solutions to those problems require knowledge and skills from at least one dominant discipline to solve with the other disciplines providing the skills, practices or tools to support the problem-solving process. This instructional framework will also focus on connections between the four disciplines and is intended to assist teachers in planning their integrated STEM activities.

The S-T-E-M Quartet instructional framework

As one of the goals of integrated STEM education is to equip learners with knowledge and skills to understand and ultimately generate solutions to the complex problems of the modern world, it is crucial to understand the characteristics of complex, persistent and extended problems and the kinds of conceptual knowledge, epistemic practices and social outcomes that integrated STEM can offer to solve these problems. Bereiter (1992) described referent-centred knowledge and problem-centred knowledge. By referent-centred knowledge, he referred to concepts and facts, sometimes referred to as declarative knowledge, that students learn. In the context of STEM, referent-centred knowledge would refer to the content that students learn in school science class, technology class, design classes and mathematics class. Bereiter argued that learning only referent-centred knowledge is limiting since it is linked with issues of verbalism, lack of students' motivation and inertness. Learning content that is independent of context and storing the knowledge does not enable learners to call the knowledge to mind and apply them to solve problems. Hence, Bereiter called for educators to focus on enabling learners to generate problem-centred knowledge since higher-order conceptual knowledge is better organized around problems rather than referents.

In order to develop problem-centred knowledge, learners need to first be presented with problems. Problems can be simple or complex, transient or persisting (Bereiter 1992). To learn higher-order conceptual knowledge in any discipline, it is important for learners to be exposed to complex as well as persisting problems so that they become organizing platforms for knowledge. As argued by English (2016, p. 359), designing "idea-generating problems"—problems that are not only "cognitively challenging", but also offer learners "multiple entry points" to engage in "reasoning and high-level thinking" about the discipline—can foster the development of content and processes central to the discipline. Furthermore, such tasks encourage collaborative problem solving and offer learners different perspectives of the same problem (Honey et al. 2014). As presented earlier, one of the goals of integrated STEM education is to nurture learners' dispositions and competencies to formulate, understand, and generate solutions to complex problems of the twenty-first century. What problem solving affords is the dual emphasis on disciplinary-specific ways of solving problems and the need to offer multi-faceted solutions to complex problems. Hence, putting problem solving at the heart of integrated STEM education potentially provides an authentic and meaningful context that motivates learning by bringing together individual disciplines, capitalizing on the knowledge and skills of each discipline to solve the complex problem.

The emphasis on authentic problems can also be found in integrated STEM education models reviewed. For example, problems and problem solving lie at the intersection of the practices proposed by the *Common Core State Standards for Mathematics* and the *Next Generation Science Standards*. Referring to Table 2, we see many common practices, such as making sense of problems, devising plans and carrying out investigations, and engaging in some form of reasoning, all of which are related to problem solving. These practices are captured by Lester and Kehle (2003) in their definition of problem solving:

> *Successful problem solving involves coordinating previous experiences, knowledge, familiar representations and patterns of inference, and intuition in an effort to generate new representations and related patterns of inference that resolve some tension or ambiguity (i.e., lack of meaningful representations and supporting inferential moves) that prompted the original problem-solving activity (p. 510).*

Table 2 Practices in the US standards for Mathematics and Sciences. Adapted from Honey et al. (2014), p. 109.

Mathematical practices	Scientific and engineering practices
Understand problems and devise solutions	Raise questions and define problems
Rely largely on abstract reasoning and quantitative solutions	Develop and use models
Construct logical arguments and apply them in the critique of reasoning by others	Plan and carry out investigations to collect empirical data
Engage mathematical modeling	Analyse and interpret data collected from investigations
Use tools (such as graphing tools etc.) strategically	Apply mathematical and computational thinking to make sense of data
Focus on precision	Craft explanations and design solutions
Look for and apply structure	Engage in argumentation from evidence
Use patterns and regularity in reasoning	Evaluate and communicate information

Although the definition was proposed for mathematical problem solving, there are commonalities in how problem solving practices are perceived in science, engineering, and technology. For instance, English et al. (2016) highlighted the processes of engineering design: problem scoping, idea creation, designing and constructing, assessing design, redesigning and reconstructing, which eventually leads to new problem scoping. These processes are similar to the model of problem solving proposed by Polya (1945), which comprises the processes of understanding the problem, devising a plan, carrying out the plan, and looking back. Likewise, scientific methods of inquiry can be seen as a problem-solving process that involves crafting a researchable question, planning an investigation (or experiment), carrying out the experiment, analyzing and interpreting the results from the experiment, constructing scientific explanations, and refining one's understanding of the question. Last but not least, computational thinking, which is an important component of the 'T' in STEM, can be seen as a set of thought processes involved in formulating problems and transforming them into forms that can be carried out effectively and efficiently by a computational tool. Table 2 compares the practices of mathematical, scientific and engineering practices which are useful to develop understanding of how the disciplines can be connected.

Our integrated STEM instructional framework builds on the fundamental perspective of solving complex, persistent and extended real-world problems using practices unique to the four disciplines, while drawing on the connections *within* and *between* disciplines. Making connections across disciplines is complex and would require teachers to handle the STEM content in a deliberate and explicit manner such that students are able to describe the connections when applying knowledge to solve real-world problems. Hence, the S-T-E-M Quartet is an instructional framework that aims to make the connections across disciplines more explicit. The four key characteristics of the framework are:

1. Problem-solving as the overarching process,
2. Complex, persistent and extended real-world problem at its core,
3. A focus on connections between the disciplines (i.e. horizontal connections), and
4. S-T-E-M as the four disciplinary domains (i.e. vertical learning) with a lead discipline.

Problem solving, instead of other frames such as design thinking, is chosen as the overarching process to encapsulate S-T-E-M since problem solving lies at the heart of all disciplines and can be argued to be the centre of design thinking (design thinking proposes a more human-centric approach to solve problems through design). Figure 1 shows the connections between the disciplines and their relationship to problems and the problem solving process.

We now elaborate the characteristics of the S-T-E-M Quartet instructional framework (referred to as Quartet henceforth).

Authentic problem core

Similar to the four models reviewed earlier, the Quartet has problems at its core. The characteristics of the

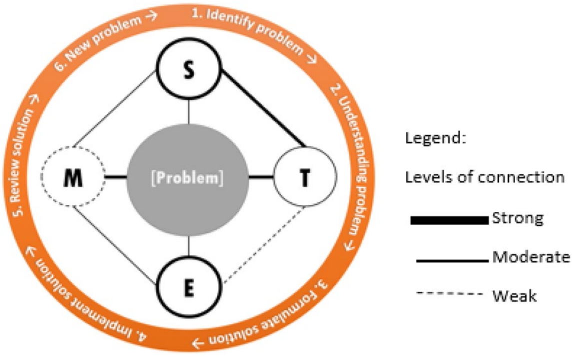


Fig. 1 S-T-E-M Quartet instructional framework

problem core of the Quartet are distinct from that of Problem-Based Learning (PBL). In PBL, it is instrumental that the problem is authentic and novel and that minimal guidance is given to the learners (Hung 2009). In the Quartet, the authenticity of the problem is defined by its practical worth and its relevance to general Science, Mathematics, Technology or Engineering principles. Guidance will be provided in the form of questions and information given to the learners. The problems of Quartet are characterized by being *persistent, complex* and *extended* (Bereiter 1992). Persistent problems are problems that recur often and hence, they are able to serve as "organizing points for knowledge." (Bereiter 1992, p. 346). To be a persistent problem, we need to go beyond routine, everyday basic level problems that only appears in worksheets and avoid problems that are forgotten once students' engagement with the task is over. Rather, persistent problems are problems of explanations that can be applied across different contexts. For instance, instead of just learning about 'falling' when observing something drop from a height, it is important that the problem allows the learners to connect between the observations of 'falling' to the concept of 'gravity'. The complexity aspect of a problem refers to the fact that problems should require knowledge and ideas from at least two disciplines to solve. These different disciplines should include knowledge from more than one of S, T, E and M and could also include knowledge and skills from other disciplines such as language and aesthetics. Complex problems also do not have an obvious single answer. Problems that can be solved by knowledge from only one discipline would not be complex from the perspective of integrated STEM. Lastly, the problem needs to be extended. Extended problems are challenging and also realistic and they require longer engagement, discussion and evaluation of the underlying principles to generate solutions. The prolonged engagement with the problem enables greater thought and retention of the principles and issues related to the problem and possible solutions generated. Figure 2 illustrates the decision making matrix to enable teachers to design problems.

Engagement in problem solving

As collaborative problem solving is integral to an integrated STEM curriculum (Honey et al. 2014), in order to generate solutions to persistent, complex and extended problems, learners need to be engaged in the process of problem solving. The engagement in this problem solving process is similar to those described in the Situated STEM Learning, STSS and Learning Standards Framework of STEAM classes. As such, the problem solving process forms the overarching frame. We follow Lester and Kehle's (2003) notion of problem solving as a generative process, common to all the core disciplines as argued earlier. In particular, the key phases of a generative problem solving process includes (1) problem identification, (2) problem understanding, (3) solution formulation, (4) solution implementation, (5) solution review, and (6) new problem generation. The last step of new problem generation is important as inspired by Polya's (1945) four-step approach to problem solving, where the last stage of Looking Back. What was missing in many of the problem solving curricula is this step of Looking Back. Looking back goes beyond checking whether the solution is right or wrong; it also involves reflecting on the solution's feasibility, potential for extension of problem/solution, and problem-finding.

The experience of problem solving will enable the learners to appreciate the interconnectedness of knowledge from different disciplines in terms of the synergies as well as tensions. The interconnected network of different knowledges will encourage alternatives, refinements of proposed solutions as well as application of referent-centred knowledge to solve the problem. In this way, students will create a collection of problem-centred knowledge related to specific contexts rather than possessing isolated problem solving skills.

Vertical learning and horizontal connections

We emphasize S-T-E-M as four disciplinary domains from which the knowledge and skills are required to generate solutions to the problems. Each discipline has their own unique epistemic practices and knowledge that learners can acquire but at the same time, it is important for learners to be familiar with how the knowledge and practices of the disciplines interact. In many ways, the Quartet is similar to the idea of a quartet in music. In music, a quartet consists of four parts, namely the soprano, the altos, the tenors, and the basses. These four parts work together to produce rich and melodious sound. While each of the parts can technically still make music on their own (just as science, mathematics, engineering and technology are legitimate disciplines on their own), the sound that is produced lacks richness and is less musical compared to a quartet. In a quartet, each part harmonizes with the other three to produce one sound. To produce that one sound, music makers utilize different mechanisms. For instance, in some songs, the soprano section brings out the melody with the support of the other three parts. Yet in other songs, the tenors could be the part that is responsible for the melody.

As with a musical quartet where one part produces the melody with the support of the other parts, the Quartet has a lead discipline when activities are designed. A problem can be designed to focus on one of the four disciplines as the dominant or lead discipline

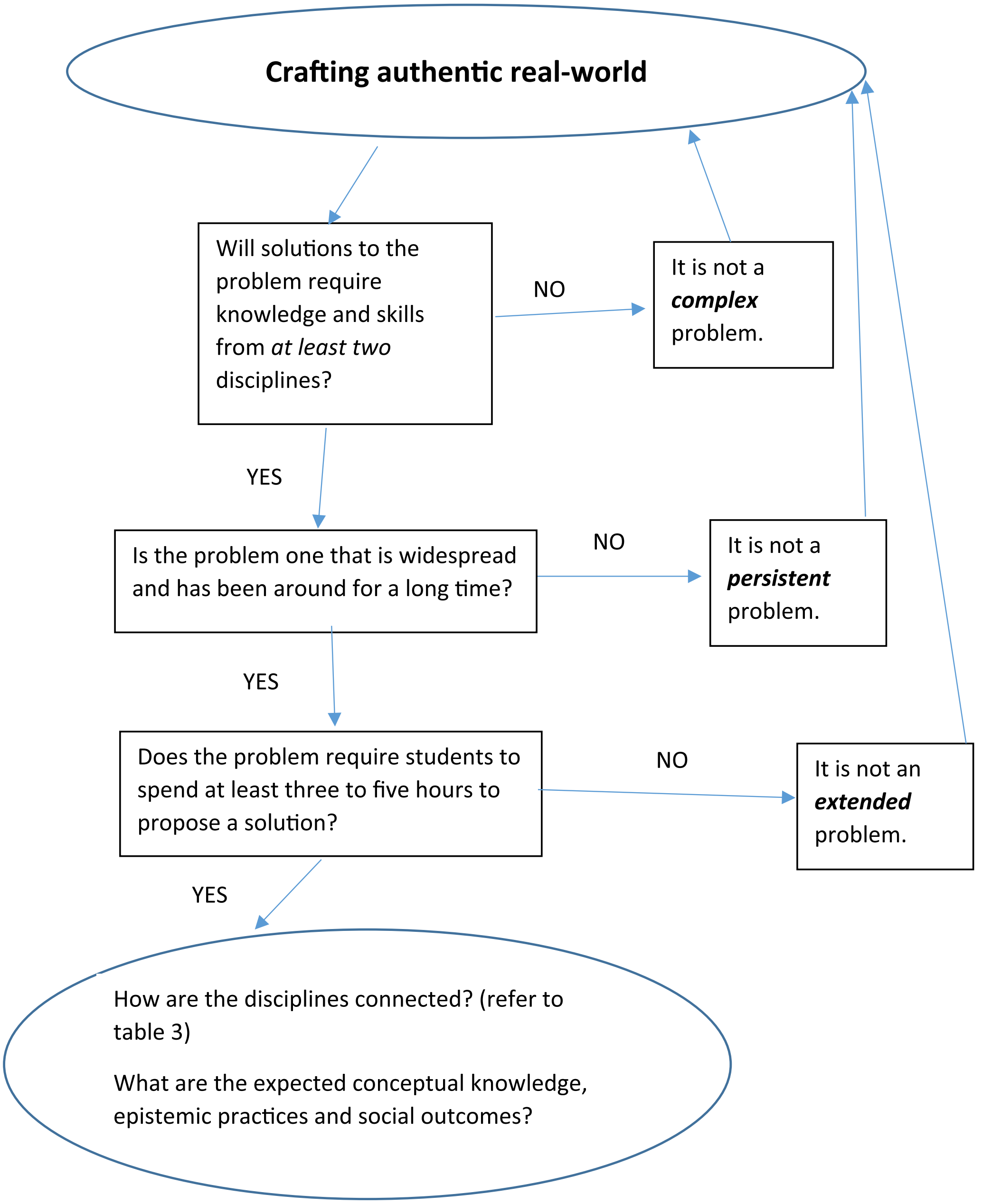


Fig. 2 Decision-making matrix for design of problem

with the other three disciplines providing the necessary skills and knowledge to solve the problem. Having a lead discipline is similar to the consideration of standard-based learning outcomes in the Framework for STEM integration in the classroom by Moore et al. (2014). The problem should be sufficiently complex so that it is not easily solved by applying a single concept in one discipline. In the process of generating the solutions, students will be guided through questions to consider and critique the connections between the different disciplines explicitly.

Finally, the Quartet is made up of vertical learning and horizontal connections. Vertical learning is characterized by the deep conceptual and epistemic learning *within* a single discipline. For instance, this could be the learning of the concepts of photosynthesis in science or algebraic equations in mathematics, or the learning of epistemic criteria for determining the soundness of a scientific claim or a mathematical proof. If the problem requires scientific knowledge and skills to solve and consequently provides learners with opportunities for in-depth learning of scientific concepts or epistemic criteria valued in science, a thick circle (refer to Fig. 1) encloses the discipline indicating steep disciplinary learning. If the problem requires the students to merely apply simple mathematical computation to solve the problem, the students would not learn in-depth specific mathematical concepts or epistemic criteria valued in mathematics. As such, the disciplinary learning in mathematics is limited and will be denoted by a dotted line.

Horizontal connections refer to the links between disciplines. Connections include application of scientific explanations, making trade-offs between criteria and constraints of an engineering design issue, using appropriate technological tools to enable mathematical modeling and using embedded sensors to provide information to optimize design in engineering. The connections between the four disciplines can be strong, moderate or weak as denoted by the thickness of the connecting lines. A strong connection is reflected by meaningful synergy of conceptual and epistemic aspects between disciplines. For instance, if the students are tasked to build a pedestrian bridge commissioned by a client, they would require science and engineering concepts such as determining stability when supporting load, properties of materials (e.g., stress, strain, and expansivity), and types of bridge designs, as well as the epistemic practices of making evidence-based decisions (in science and engineering) and making tradeoffs between various criteria and constraints (in engineering), such as stability, material strength, building cost, client needs, etc. (Cunningham and Kelly 2017). As such, the connection between the disciplines of science and engineering will be strong and denoted by a thick line. A moderate connection is denoted by cross-disciplinary synergies involving either the conceptual or epistemic aspect. For instance, if students were asked to predict the otter population in Singapore in 5 years' time, students would need to understand scientific concepts such as food webs and factors affecting population growth as well as mathematical models (e.g., linear and exponential relationships). This connection between science and mathematics is a moderate one as it involves conceptual aspects but not epistemic aspects of science and mathematics (e.g., if students are not required to determine the best model). Finally, there can also be weak connections between the disciplines defined by a dotted line. This includes using different computer software to record data in scientific experiments. Application of a computer software as a tool in the problem solving process without understanding how the software works is considered a weak connection between disciplines. Table 3 characterises the connections between two disciplines that teachers can consider when they are crafting the problem. As a guide, a strong connection is one that have all the three applications used when students are engaged with solving the problems. There is moderation connection between two disciplines should the problem only require students to engage in two of the three activities. If students only use one of the three applications in solving the process

Table 3 Characterizing connections between disciplines

Connections between disciplines	Description
S–T	Application appropriate technological tools to seek causality or to investigate relationships between different variables Application technological tools to automate or increase accuracy of evidence collected Application technology to create simulations or create models to represent scientific phenomena
S–E	Application conceptual knowledge and models of science to seek understanding of the functions of design Application of scientific knowledge to search for better outcomes Application of evidence from scientific inquiry to inform and interpret success of solutions
S–M	Application of mathematical models to share and evaluate scientific knowledge and models Using mathematical formulation to seek understanding of scientific phenomena Application of mathematical tools to represent data collected during scientific investigations
T–E	Construction of models or prototypes using technologies for a specific purpose or product Application of engineering design to create or enhance technological solutions Application of technological tools to evaluate and inform engineering solutions
T–M	Application of mathematical models to create technological algorithms Application of technological tools to create mathematical models using large data Application of technological tools to interpret complex mathematical issues to transform them from raw to refined, simple to complex and ill-defined to well-defined (Morrison-Love 2017)
E–M	Application of precision from mathematical computation in the design of solutions Application of patterns and regularity in reasoning to define and justify designs Application of mathematical tools to collect data to search for refinement and improvement of design

of problem solving, then there is a weak connection between the disciplines. If there is no applications used, there is no connection between the disciplines.

Further, in considering the strength of connections between the lead discipline and the other disciplines, there are four different possibilities as reflected in Table 4. The connections are considered in terms of the conceptual knowledge, epistemic practices and skills of the disciplines.

Application of the S-T-E-M Quartet instructional framework

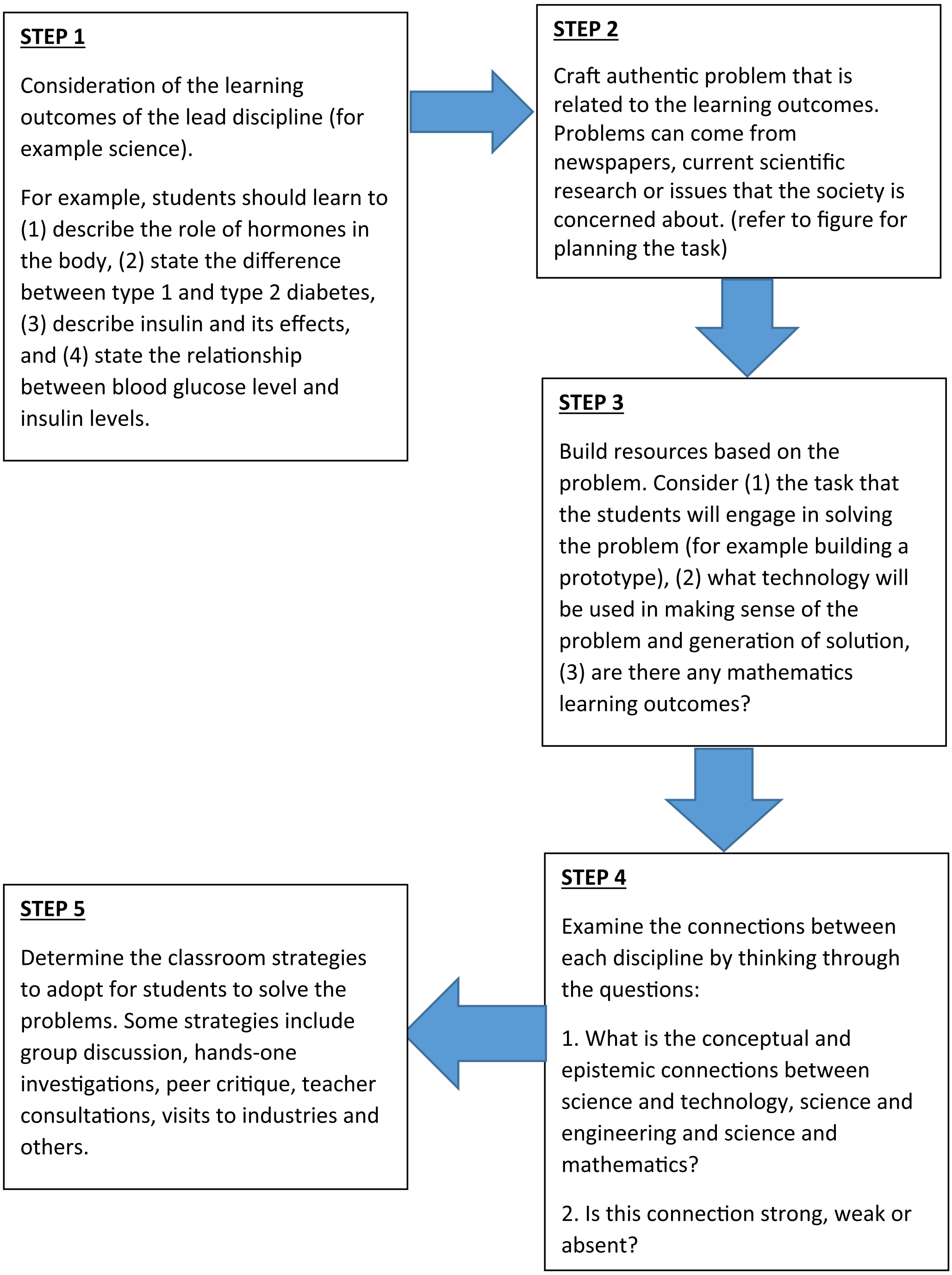
Applying the S-T-E-M Quartet instructional framework

The Quartet can be used as both a guide to enable design of tasks as well as an evaluation tool to assess STEM tasks. In Fig. 3, we illustrate how principles from the Quartet can be used as a planning guide and evaluation tool for STEM tasks.

To illustrate how the Quartet is applied to plan an integrated STEM lesson in high school biology, Fig. 4 shows a STEM task focusing on the problem of insulin delivery for diabetic patients. With biology as the lead discipline and the concepts of hormone (insulin) and its role in management of diabetes, a task is crafted with science learning as the core. The problem is persistent since it is targeted at the principles of drug delivery systems into the body and deals with a global epidemic. The complexity of the problem lies in the fact that the solution does not just reside purely on the design of the delivery system. It requires the learners to think about the severity of the patients' conditions, their lifestyles, age and socioeconomic status. Finally, the problem is extended as learners are required to read, research and discuss the 'case' in-depth before they can design the prototype. This is an example of a StEm task with strong connections between S–E, moderate connections between E–M and S–T, and weak connections between S–M and M–T. In the implementation, students engaged in the task by first understanding and critiquing the current solutions available for insulin delivery. Four possible solutions were presented to the students—(1) insulin delivery pens, (2) insulin pumps, (3) inhaled insulin (Afrezza), and (4) V-Go device. Students examined each of the solutions and identify the limitations or problems with each existing solution. They described the limitations/problems in detail. Subsequently, they formulated a solution by designing a prototype that would overcome the limitations (identified by the students) of the existing solutions. After they have designed the solutions, they presented the solutions or tested out the solutions. The proposed solutions were tested and subjected to peer critique. After testing and critique, the students refined their solution. For example, one team of students proposed an insulin eye drop with an irreplaceable teat. The critique to that design was that it could potentially cause an eye infection to the users. The students subsequently changed their design to a disposable teat that was washable and could be reused for a week so that the solution was also environmentally sustainable. As such, by engaging in the problem-solving of the insulin delivery problem, students learnt the content of homeostasis and applied the engineering design thinking cycle to improve upon their design. They also applied some mathematical and technological skills in the process of solving the

Table 4 Different connections in STEM

Levels of integration	Number of disciplines with strong connections	Description
STEM	4	Conceptual knowledge, epistemic practices and skills of all *four* disciplines are required to solve the problem. Any missing discipline would render the problem unsolvable
STEm, STeM, StEM, sTEM,	3	Conceptual knowledge, epistemic practices and skills of *three* disciplines are required to solve the problem. Knowledge and skills of the last discipline is either not required or used merely as a tool in the problem solving process
STem, StEm, SteM, sTEm, sTeM, stEM	2	Conceptual knowledge, epistemic practices and skills of *two* disciplines are required to solve the problem. Knowledge and skills of the two other disciplines are either not required or used merely as a tool in the problem solving process
Stem, sTem, stEm, steM	1	Conceptual knowledge, epistemic practices and skills of only *one* discipline is required to solve the problem. Knowledge and skills of the other discipline are either not required or used merely as a tool in the problem solving process. When there is only one discipline, this is NOT considered a complex problem. In such a situation, the problem needs to be re-evaluated
Stem	0	All the disciplines are used but the problem is not anchored in one specific discipline. A superficial form of integration of the disciplines takes place. Similar to the situation described above, the problem here is NOT a complex problem and will need to be evaluated



STEP 1

Consideration of the learning outcomes of the lead discipline (for example science).

For example, students should learn to (1) describe the role of hormones in the body, (2) state the difference between type 1 and type 2 diabetes, (3) describe insulin and its effects, and (4) state the relationship between blood glucose level and insulin levels.

STEP 2

Craft authentic problem that is related to the learning outcomes. Problems can come from newspapers, current scientific research or issues that the society is concerned about. (refer to figure for planning the task)

STEP 3

Build resources based on the problem. Consider (1) the task that the students will engage in solving the problem (for example building a prototype), (2) what technology will be used in making sense of the problem and generation of solution, (3) are there any mathematics learning outcomes?

STEP 4

Examine the connections between each discipline by thinking through the questions:

1. What is the conceptual and epistemic connections between science and technology, science and engineering and science and mathematics?

2. Is this connection strong, weak or absent?

STEP 5

Determine the classroom strategies to adopt for students to solve the problems. Some strategies include group discussion, hands-one investigations, peer critique, teacher consultations, visits to industries and others.

Fig. 3 Apply the S-T-E-M Quartet instructional framework to plan integrated STEM activities

problem. Figure 4 illustrates the strength of connections across different disciplines as well the depth of vertical learning within a single discipline.

Comparing with the four existing models, the value of the Quartet lies in making explicit the connections between the disciplines. The Quartet bears much resemblance to Moore et al. (2014) Framework for STEM integration in the classroom and can be considered an enhancement of the Moore et al. framework. It is similar to the situated STEM Learning, the STSS and the Learning Standard Framework of STEAM classes in the problem solving process. By building on and improving

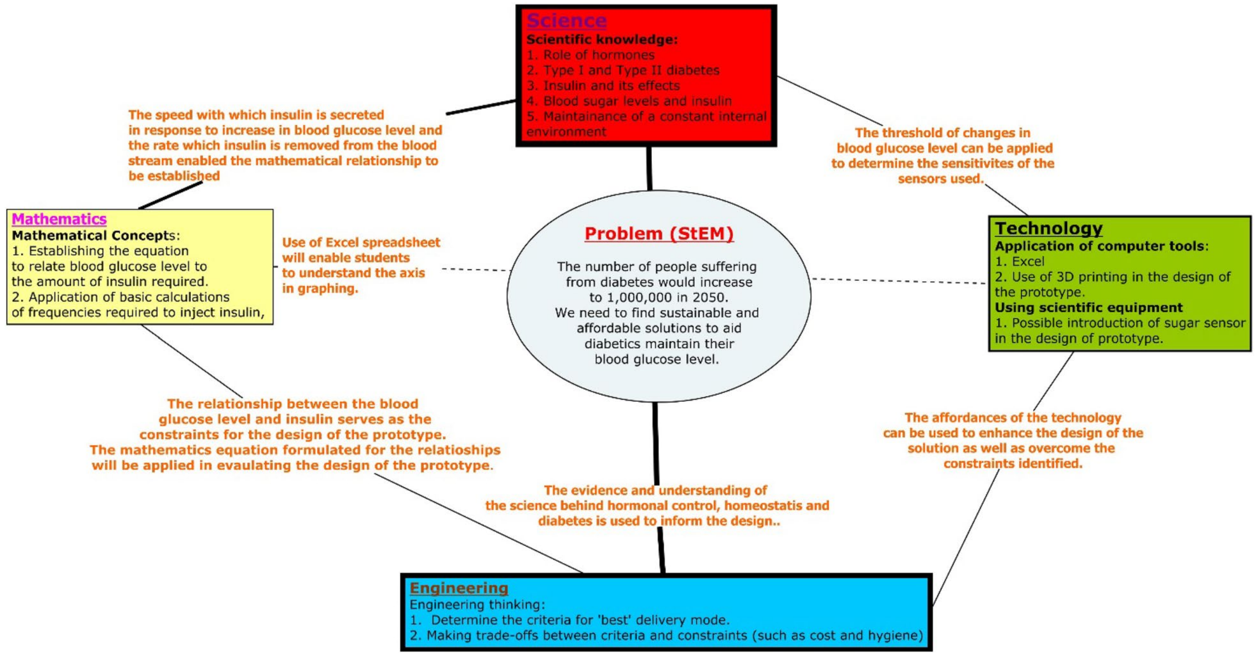


Fig. 4 STEM task centred on solving the problem of insulin delivery for diabetic patients

existing frameworks, we hope to add to the conversation in the community of STEM scholars as we collectively work towards a consensus of a robust yet flexible framework for integrated STEM.

Conclusions

This paper compared four different instructional frameworks for STEM education and found that the frameworks compared lacked a focus on connections between the different disciplines. As such, the S-T-E-M Quartet instructional framework was proposed as a way to help teachers think about how the different discipline are connected and if the connection is weak, moderation or strong. Focusing on how the disciplines are connected enables teachers to better appreciate if the disciplines are connected through conceptual knowledge, epistemic practices or social norms. Knowledge of the levels of connection between disciplines would also ensure that the integration is not random or contrived but is based on legitimated ways to solve specific problems.

Comparing the Quartet to the seven areas of focus mentioned in Table 1, the Quartet is focused on authentic real world problems, it anchors on standard based learning outcomes, abd places emphasis on connections between disciplines. The consideration of science inquiry and engineering practices is taken into consideration in the vertical learning components *within* each discipline. The consideration for twenty-first century skills and context is embedded within the problem-solving process but can be rather limited in emphasis.

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Authors' contributions
This manuscript is the joint effort of all the four co-authors. A-LT lead in the writing and contributed to the concept of disciplinary and STEM models. T-WT and Y-SO were responsible for the elements of connections in terms of epistemic practices, conceptual knowledge and social outcomes. B-HC was responsible for the problem solving and mathematics aspects. All authors read and approved the final manuscript.

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